

# Tool for Automatic Measurement of Equivalent width (TAME)

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## ABSTRACT

We present a tool for measuring the equivalent width ( $EW$ ) in high-resolution spectra. The Tool for Automatic Measurement of Equivalent width (TAME) provides the  $EW$ s of spectral lines by profile fitting in the automatic or the interactive mode, which can yield a more precise result through the adjustment of the local continuum and fitting parameters. The automatic  $EW$  results of TAME have been verified by comparing them with the manual  $EW$  measurements by IRAF `splot` task using the high-resolution spectrum of the Sun, and measuring  $EW$ s in the synthetic spectra with different spectral resolutions and S/N ratios. The  $EW$ s measured by TAME agree well with manually measured values, with a dispersion of less than  $2 \text{ m}\text{\AA}$ . By comparing the input  $EW$ s for synthetic spectra and  $EW$ s measured by TAME, we conclude that it is reliable for measuring the  $EW$ s in a spectrum with a spectral resolution,  $R \gtrsim 20000$  and find that the errors in  $EW$ s is less than  $1 \text{ m}\text{\AA}$  for a S/N ratio  $\gtrsim 100$ .

*Subject headings:* methods:data analysis — techniques:spectroscopic — stars:fundamental parameters

## 1. Introduction

The measurement of equivalent width ( $EW$ ) for spectral absorption lines is essential in a spectral analysis, particularly for determining the atmospheric parameters and chemical abundances of stars. In the study of stellar spectroscopy, it is critical to determine the atmospheric parameters of stars, such as the effective temperature ( $T_{\text{eff}}$ ), surface gravity ( $\log g$ ), metallicity ( $[\text{Fe}/\text{H}]$ ), and micro-turbulence ( $\xi_t$ ), because atmospheric parameters are fundamental to understand spectroscopic properties and construct the model atmosphere for an abundance analysis. For the atmospheric parameters, however, the most common method is to analyse the abundances that can be obtained from  $EW$  measurements of neutral and singly ionized lines. Additionally, the chemical abundances are also estimated by measuring the  $EW$ s of atomic lines (e.g., Bensby et al. 2003; Santos et al. 2004; Bond et al. 2006; Gilli et al. 2006; Sousa et al. 2006; Kang et al. 2011). The  $EW$  measurement, therefore, is undoubtedly the most important task in spectroscopic studies.

The  $EW$ s of spectral lines have generally been measured by using the `splot` task in IRAF<sup>1</sup> `echelle` package, which makes it possible to manually estimate the  $EW$  of each line. Although this method guarantees a high degree of accuracy for  $EW$  measurement, it requires a disciplined expert in the field of stellar spectroscopy and the result depends on the personal bias. For an abundance analysis, it is necessary to measure the  $EW$ s for many lines for each star, which is a tedious and time-consuming task. Therefore, a uniform and fast method for  $EW$  measurement is required in stellar abundance studies using a large number of high-resolution spectra.

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<sup>1</sup>IRAF is the Image Reduction and Analysis Facility software. It is written and supported by the IRAF programming group at the National Optical Astronomy Observatories (NOAO) that is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the National Science Foundation

Sousa et al. (2007) presented a new C++ code, called ARES (Automatic Routine for line Equivalent widths in stellar Spectra), which can automatically and simultaneously measure the *EWs* of spectral lines in stellar spectra. ARES provides quick measurement results for *EWs*, without manual operation, from high-resolution spectra. However, ARES code focuses on the performance of the code, and hence deprives a user of the interactive operation that can be used to control an environment for each line. Further, a Fortran code for *EW* measurement, called DAOSPEC, was recently presented by Stetson & Pancino (2008). In order to achieve more accurate measurement, DAOSPEC offers the enhanced interactive mode for detailed manipulative tasks, such as the adjustment of the local continuum and the deblending of nearby lines. Unfortunately, ARES and DAOSPEC were written in C++ and Fortran, respectively. Therefore, the installation of ARES and DAOSPEC depends on the platform OS, and it would be difficult and inconvenient to compile and run these codes coherently, because of the required libraries (e.g., cfitsio<sup>2</sup>, GSL<sup>3</sup>, SuperMongo<sup>4</sup>, IRAF).

To avoid these practical difficulties, we have developed the Tool for Automatic Measurement of Equivalent width (TAME)<sup>5</sup>, which is written in IDL<sup>6</sup> and uses a graphical user interface (GUI). TAME can be used with any platform OS on which IDL has been installed, and it contains various features required to adjust the environment of *EW* measurement such as the local continuum and radial velocity of a star. Its semi-automatic

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<sup>2</sup><http://heasarc.nasa.gov/fitsio/fitsio.html>

<sup>3</sup><http://www.gnu.org/s/gsl/>

<sup>4</sup><http://www.astro.princeton.edu/~rhl/sm/sm.html>

<sup>5</sup>TAME can be downloaded from <http://astro.snu.ac.kr/~wskang/tame/>

<sup>6</sup>The Interactive Data Language (IDL) is a cross-platform software, providing support for Microsoft Windows<sup>®</sup>, Mac OS X, Linux, and Solaris (<http://www.exelisvis.com>)

mode (*hereafter*, the interactive mode) offers more flexible measurement of the  $EW$  as similar to DAOSPEC. And its fully automatic mode (*hereafter*, the automatic mode) can simultaneously measure the  $EW$ s for a large set of lines. TAME produces a formatted text file containing the  $EW$  result which can be used directly in the abundance analysis code MOOG (Snedden 1973), in addition to a graphical output file with the fitting results of the local continuum and line profile.

In this work, we describe the procedure by which TAME measures the  $EW$ s of spectral lines and examine the results of  $EW$ s obtained by TAME. In Sect. 2, we introduce the user interface and input parameters of TAME. In Sect. 3, we explain the automatic processes used to measure the  $EW$  with TAME, such as determining the local continuum, searching for blended lines, and fitting the lines with a Gaussian/Voigt profile. In Sect. 4, we present the comparison of the manual  $EW$  measurements obtained using IRAF and those obtained using TAME for the high-resolution spectra of the Sun, whose atmospheric parameters are well known. We also discuss the difference between the  $EW$  estimated by TAME and the input  $EW$  for a synthetic spectrum having different spectral resolutions and S/N ratios. In Sect. 5, we summarize the advantages of using TAME along with its performance results.

## 2. Interface and Input Parameters

The inputs, outputs, and user interface of TAME are shown in Figure 1. Initially, TAME requires the spectrum data in text format and the line list file that contains the line information such as the wavelength, element index (for MOOG code; e.g. "26.0" for Fe I), excitation potentials (eV), and oscillator strength ( $\log gf$ ). The other parameters for  $EW$  measurement are obtained from the formatted text file, which contains parameters such as the spacing of wavelength (SPACING), SNR for determining local continuum (SNR), smoothing factor (SMOOTHER), and measurable minimum  $EW$  (MINEW).

The SPACING parameter restricts the wavelength window, which is used for determining the local continuum and searching for the lines. The SNR parameter is related with the cut-off ratio when the local continuum level is being determined. The SMOOTHER parameter is applied to the spectrum in order to mitigate the effect of noise while searching for the lines using numerical derivatives. The smoothed spectrum and its derivatives allow the correct lines to be detected in the spectrum even for a low S/N ratio.

TAME is a GUI-based program that provides the plots of the local continuum and the fitting result as shown in Figure 1. The GUI consists of the parameter panel (*top*), the interactive panel for adjusting the local continuum (*middle*), and the plotting panel of the line-fitting results and its residuals (*bottom*). TAME presents the automatic result of the *EW* measurement that can be interactively adjusted by user. Essentially, it has been designed to provide a convenient *EW* measurement for a large number of absorption lines in a high-resolution spectrum. It presents the spectrum near the target line and the information of nearby lines adopted from Vienna Atomic Line Database (VALD, Kupka et al. 2000, 1999; Ryabchikova et al. 1997; Piskunov et al. 1995). After verifying an automatic result, the user can decide whether the *EW* of the line is reliable. If the user prefers, the user can correct the local continuum and adjust the parameters for fitting, such as fitting function (Gaussian/Voigt), smoothing factor, and radial velocity. In the automatic mode, TAME can also calculate the *EWs* of all target lines simultaneously, based on the default options described in the formatted parameter file.

### 3. Methods

TAME measures the *EWs* of spectral lines with following steps:

1. Determine the local continuum near the target line

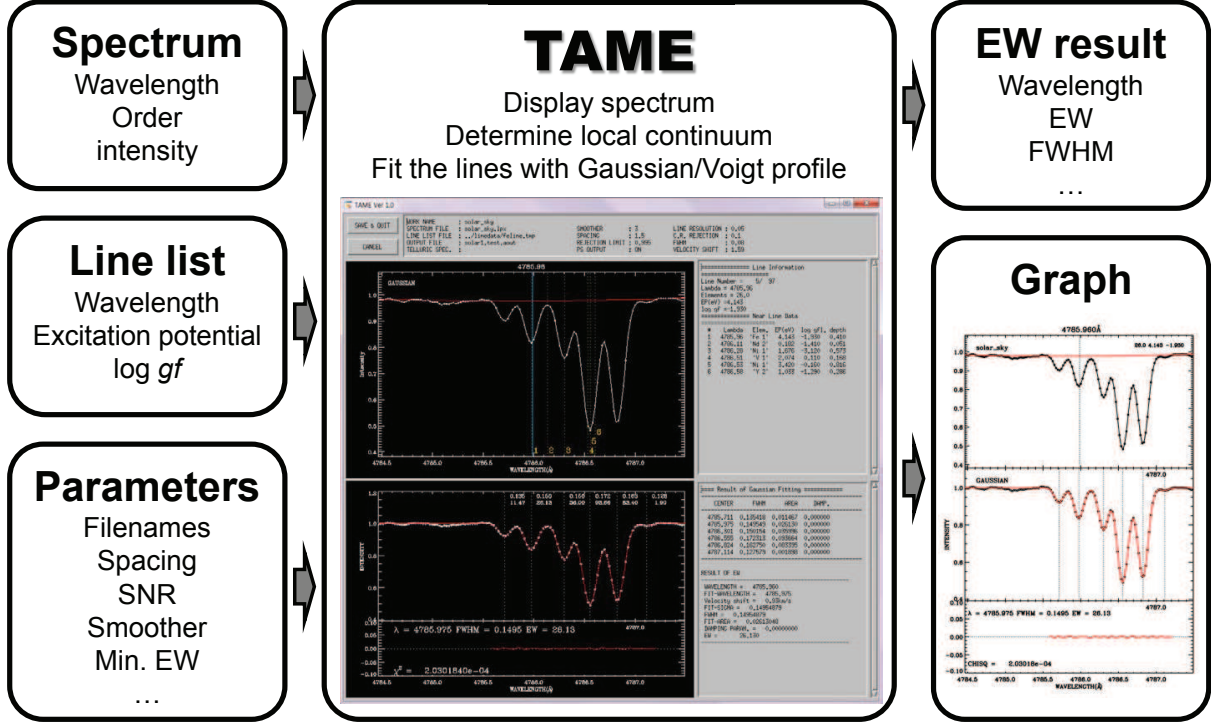


Fig. 1.— Inputs, outputs, and user interface in TAME program.

2. Normalize the local spectrum with the local continuum
3. Identify the lines near the target line in the normalized spectrum
4. Fit the target line with the Gaussian/Voigt profile with deblending, if required
5. Estimate the  $EW$ , FWHM, and the center wavelength of the target line from fitting.

In this section, we describe the main processes of the TAME program in detail, such as determining the local continuum level, searching for the lines, and fitting the target line with the sample synthetic spectrum, which has a resolving power of  $R = 10000$  and a S/N ratio of 100. We selected the resolving power and the S/N ratio of synthetic spectra as the lower limit of which TAME works acceptably. Then, we briefly discuss the two types of output files generated by TAME and demonstrate how TAME works for actual spectra by

using the examples of metal-rich and metal-poor stars.

### 3.1. Determining the Local Continuum

TAME determines the local continuum near the target line according to the following steps:

1. Find the fitting curve in the trimmed spectrum by using the SPACING parameter with a polynomial function (order = 2)
2. Cut off the points below  $(the\ curve) \times \{1 - 2/(\text{SNR parameter})\}$
3. Derive a new curve by polynomial fitting with the residual points after the cut-off
4. Iterate step 2 – 3 until no points remains that need to be cut off

We verified the process employed to determine the local continuum by using a synthetic spectrum whose S/N ratio = 100, for different SNR parameter values of 200, 100, and 50 (Figure 2). If the S/N ratio were 100 and the noise followed a normal distribution, the  $\sigma_{noise}$  of the continuum in the normalized spectrum would be 0.01 ( $= \sigma_{noise} = 1/\text{SNR}$ ). Therefore, we would obtain the final data points representing the local continuum after recursively cutting off the points below the  $2\sigma_{noise}$ <sup>7</sup> value of the polynomial fitting curve. Factually, we cannot completely reproduce the original continuum of the spectra only from the observed data. It would only be possible to predict the practical local continuum by using S/N ratio of the observed spectrum. When using the SNR parameter = 100 (Figure 2b), we found

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<sup>7</sup>If noise follows a normal distribution, after the iterations, points in the upper 50% (all points above the fitting curve) and lower 47.7% (the points between the fitting curve and its lower  $2\sigma_{noise}$ ) will remain on the final local continuum.



that the final local continuum had a good agreement with the original local continuum, which was supposed to be unity, within a deviation of around 0.3% ( $\sim 0.003$ ). The standard deviation of the residual points (*black*) after iterations was very close to 0.01 (= S/N ratio of the synthetic spectrum). In the other cases, in which the SNR parameter = 200 and 50 (Figure 2a and 2c), the final local continuum appeared to be more curved than that for SNR = 100. In Figure 2a, the local continuum is determined at 0.5% higher than the original continuum, and moreover, the shape of the continuum is highly tilted around the target line. This large discrepancy near the boundary region is because a large number of points were excluded by the input parameter condition, SNR = 200. In contrast, as shown in Figure 2c, when a large number of points were included for continuum fitting, their continuum severely descended around the center.

The local continuum problem is one of the main causes of *EW* errors (Stetson & Pancino 2008). Moreover, the errors arising from the local continuum cannot be completely quantified or predicted even though they are known to exist. Hence, the best method to determine the local continuum is visually, by experts who are highly disciplined with the stellar spectrum. However, it would be inefficient and time-consuming to visually examine the local continuum for hundreds of lines only by eyes.

Therefore, TAME enhances the process used to determine the local continuum by using the interactive mode. TAME initially suggests the local continuum near the line, which is automatically determined by SNR parameter. This local continuum level, which is numerically estimated, can be finely tuned by the user’s interaction. By pressing the “u” or “l” key, the local continuum level can be shifted up or down proportional to one fifth of  $1/(\text{SNR parameter})$ . Eccentric points, which are suspected to be produced by the contamination from cosmic rays or bad pixels, can be excluded manually by pressing the “d” key for that point. When the “c” key is pressed, TAME enters the custom mode, which

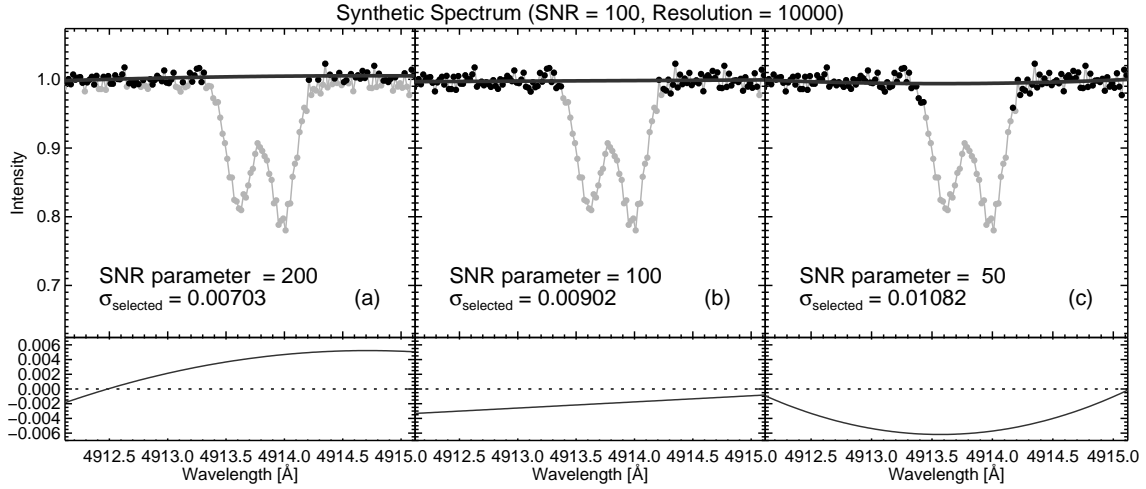


Fig. 2.— The local continuum fitting result for each SNR input parameter ( $= 200, 100, 50$ ). The *gray* points show the original synthetic spectrum with SNR = 100, and the *black* points represent those selected by the SNR input parameter for local continuum fitting. The plots at the *bottom* show the residuals between the original continuum of synthetic spectra ( $= 1$ ) and the local continuum determined by each SNR parameter.

makes it possible to add points anywhere the user wants. This adjustment is then directly applied to the fitting result, and hence, it can be quickly verified by the user without the requirement of further operations.

### 3.2. Identifying the Lines

After determining the local continuum, TAME numerically identifies the absorption lines in the normalized spectrum. For detecting the center of the line in an arbitrary spectrum, we adopted the method that uses the numerical derivatives and has been suggested by Sousa et al. (2007). TAME identifies the line center using the following steps:

1. Determine the region for searching for lines, which appears to include all blended lines

with the target line

2. Calculate the  $2^{nd}$  and  $3^{rd}$  derivatives of the normalized spectrum smoothed with the SMOOTHER parameter
3. Find the transition points in the wavelength, where the  $3^{rd}$  derivative changes from positive to negative near the local maximum of the  $2^{nd}$  derivative
4. Calculate the exact wavelength using the linear interpolation near the transition points

The numerical derivatives become much more noisy than the original spectrum, because of the noise divergence in a numerical calculation. Figure 3 shows how the noise in the spectrum diverges in the cases without or with smoothing. Even when the noise is extremely small in the normalized spectrum, it rapidly multiplies in each numerical derivative calculation. In the case of no smoothing (Figure 3a), much more lines are identified due to the noisy derivatives, which is amplified in each step of calculation. When the spectrum and derivatives were smoothed with 3 or 5 points<sup>8</sup> (Figure 3b and 3c), TAME properly detected two of the correct absorption lines even though the two lines were blended with each other. The input wavelengths of these two lines in the synthetic spectrum are 4913.62 and 4913.98 Å, and TAME finely estimated the wavelengths of these lines at 4913.61 and 4913.99 Å with an error of only 0.01 Å.

### 3.3. Gaussian/Voigt Fitting

After searching for absorption lines, TAME calculates the *EW* of the target line by fitting with a Gaussian/Voigt profile. Based on the wavelengths of detected lines through

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<sup>8</sup>We used a boxcar average for smoothing,  $R_i = \frac{1}{w} \sum_{j=0}^w I_{i+j-w/2}$ ,  $w$  = smoothing width

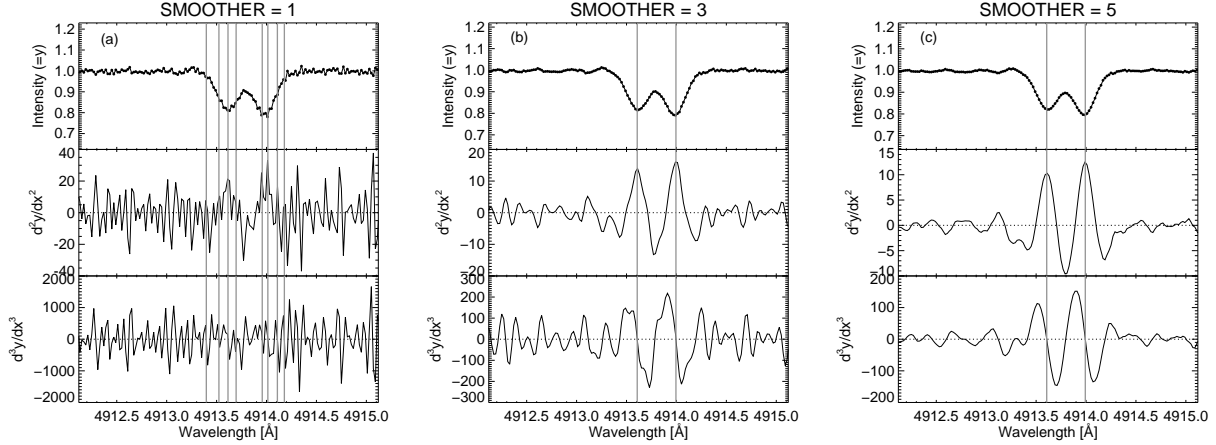


Fig. 3.— The numerical 2<sup>nd</sup> and 3<sup>rd</sup> derivatives of the synthetic spectrum for each smoothen parameter (= 1, 3, 5). The synthetic spectrum used for the test has a resolving power of 10000 and a S/N ratio of 100.

the previous processes, TAME finds the best-fitting of the spectral lines by least-squares curve fitting with the `mpfit` IDL library<sup>9</sup>. TAME outputs the *EW* and FWHM of the spectral line as follows:

1. Generate the model functions of spectral lines based on the number of detected lines.

For example, if two lines are detected and the user plans to use a Gaussian profile, TAME makes the model functions including two Gaussian profiles.

$$\mathcal{F}_{model} = 1 - \sum_{i=1}^2 \text{Gaussian}(\text{wavelength}_i, \text{FWHM}_i, \text{EW}_i) , \quad (1)$$

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<sup>9</sup>Markwardt IDL library by Craig Markwardt. Fitting routines are described in the web-page of <http://www.physics.wisc.edu/~craigm/idl/idl.html>. For least-squares curve fitting, MPFIT library used the Levenberg-Marquardt algorithm (LMA), originated from MINPACK Fortran library written by Jorge Moré, Burt Garbov, and Ken Hillstrom.

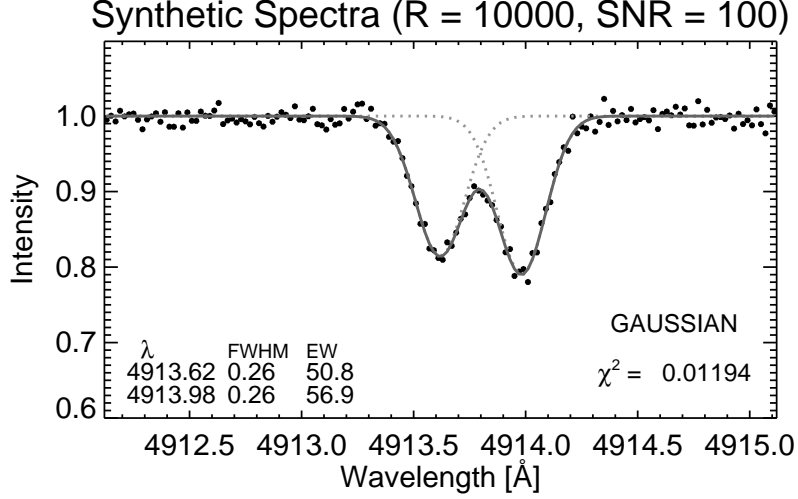


Fig. 4.— The result of Gaussian profile fitting. The *gray* solid line indicates the best-fitting result for all lines and the *gray* dotted line represent the fitting profile of each line component.

2. Set the initial value and the range of each parameter such as the wavelength and FWHM.
3. Find the best fit by starting with the initial value of each parameter.

Figure 4 shows the fitting results of the synthetic spectrum for a Gaussian profile. As shown in Figure 4, TAME estimates the centers of two lines at 4913.62 and 4913.98 Å by Gaussian profile fitting, and obtains the *EWs* of those lines at 50.8 and 56.9 mÅ. Considering that the input *EWs* of these lines are 49.8 and 56.2 mÅ, the estimated *EWs* are in very good agreement with the input *EWs*, having differences within only 1 mÅ. We confirmed that despite of the line deblending, TAME can estimate the accurate *EWs* in the synthetic spectrum with  $R = 10000$  and the S/N ratio = 100.

### 3.4. Outputs

After the completion of the *EW* measurement, TAME outputs a text file and a graphical post-script file. The text output file is written in the same format as the input file of the **abfind** driver of MOOG code (Snedden 1973), in order that the user can instantly calculate the abundances of lines using MOOG code. This text output also contains the line center and FWHM of the fitting profile, and the radial velocity calculated by the difference between the rest-frame wavelength and the measured wavelength for each line. The representative radial velocity of the star can be derived by averaging the radial velocities of individual lines along with their standard deviation. Additionally, the FWHM of the line and the  $\chi^2$  value from the fitting could be used for the diagnostics of lines. Each atomic spectral line has a specific FWHM for each wavelength, atomic mass, and stellar effective temperature. Extremely broad or extremely narrow lines, relative to the others, can be expected to be affected by obscure lines or to not originate from the stellar atmosphere, and therefore, they can be neglected in the *EW* results. This is because the broad lines, that are closely blended each other, cannot be deblended due to the limit of the spectral resolution.

The graphical output file shows the spectrum and fitting plots of the local continuum and the line profile for each line. Because TAME generates these plots in a post-script file, the user can easily open and print this graphical output. When performing the abundance analysis, the graphical output is very useful for checking whether the abundance of each line is well determined. The *EW*s of more than tens of lines are generally adopted for the chemical abundance of one element. If the abundance of a line is located far from the abundance distribution of the other lines of the same element, the graphical output can help with inspecting the spectrum around aberrant lines and their fitting plots.

### 3.5. Examples using the Spectra of Metal-rich and Metal-poor Stars

We examined the process of  $EW$  measurement performed by TAME with the actual spectra of HD 75732 ( $[Fe/H] = +0.35$ ) as a metal-rich star and HD 155358 ( $[Fe/H] = -0.63$ ) as a relatively metal-poor star. These spectra were obtained with the BOAO Echelle Spectrograph (BOES) (Kim et al. 2002, 2007) in 2008 and have the spectral resolution  $R = 30000$  and an S/N ratio of  $\sim 200$  (Kang et al. 2011).

Figure 5 shows the local continuum fitting results for the Fe I line at  $5250.22 \text{ \AA}$  for two sample stars. For the metal-rich star HD 75732, the central region of the local continuum appears to sink below about 2%, relative to the side region. This is, as mentioned above, because of the undersampling of the points that are used to determine the local continuum in this spectral region. It is difficult to manage this bending local continuum in a crowded region with computational manipulation, because neglecting a very large number of points by a statistical method might produce an unstable fitting result. The best solution for metal-rich stars such as HD 75732, is to confirm the fitting results visually and to correct them through manual interaction. Further, we observed that the local continuum of the metal-poor star HD 155358 was well determined.

Figure 6 illustrates the fitting results with Gaussian and Voigt profiles. For the test, we plotted the fitting results of all the lines near the target line beyond the region that appeared to be blended with nearby lines. In normal cases, TAME automatically defines the blended region by comparing the line features with the local continuum level, and performs fitting only with the points in that region. In the case of HD 75732, it can be seen that there are several lines that do not match the Gaussian profile. The line at  $5249.08 \text{ \AA}$  seems to be blended with a weak line, which cannot be detected by the method that uses numerical derivatives. The  $EW$ s of two lines at  $5250.22 \text{ \AA}$  and  $5250.65 \text{ \AA}$  are more than  $100 \text{ m\AA}$ , and hence, show a better fitting result when a Voigt profile is used. On the contrary,

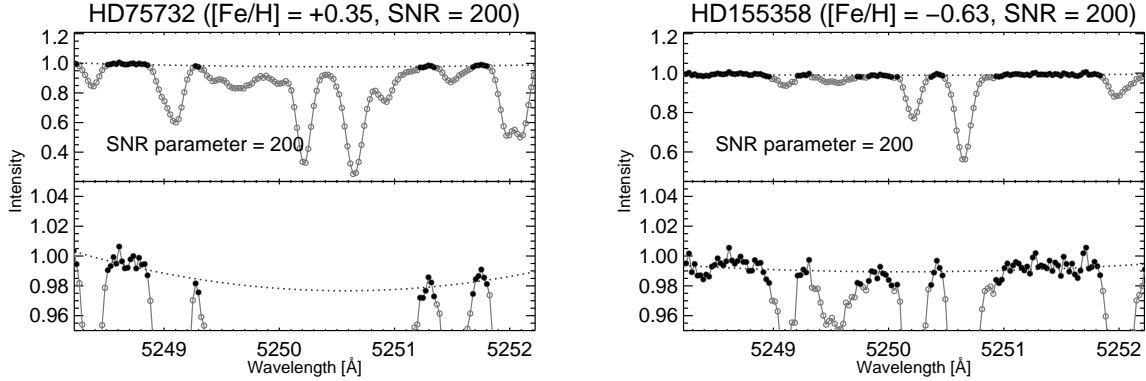


Fig. 5.— The determination of the local continuum for the two cases of a metal-rich and a metal-poor star, i.e., HD 75732 and HD 155358. The *lower* panels show the magnifying results around the continuum.

the fitting result of the metal-poor star HD 155358 shows a better  $\chi^2$  and fitting result for a Gaussian profile, because the lines for this star are much weaker than those of metal-rich HD 75732.

As a result, it can be concluded that TAME appears to work acceptably for metal-poor stars, even in the automatic mode, and that careful adjustments in the interactive mode might be required for metal-rich stars or for strong lines.

#### 4. Results

The *EW* result of TAME has been validated by comparing it with the *EWs* measured by IRAF `splot` task, and by applying TAME to various synthetic spectra. The *EWs* in the solar spectrum have been manually measured by IRAF `splot` task and automatically estimated using TAME. Then, we observed whether TAME is appropriate for the abundance analysis by investigating not only the difference in the *EWs* but also the atmospheric parameters derived with those *EWs*. In order to evaluate the reliability for a variety of



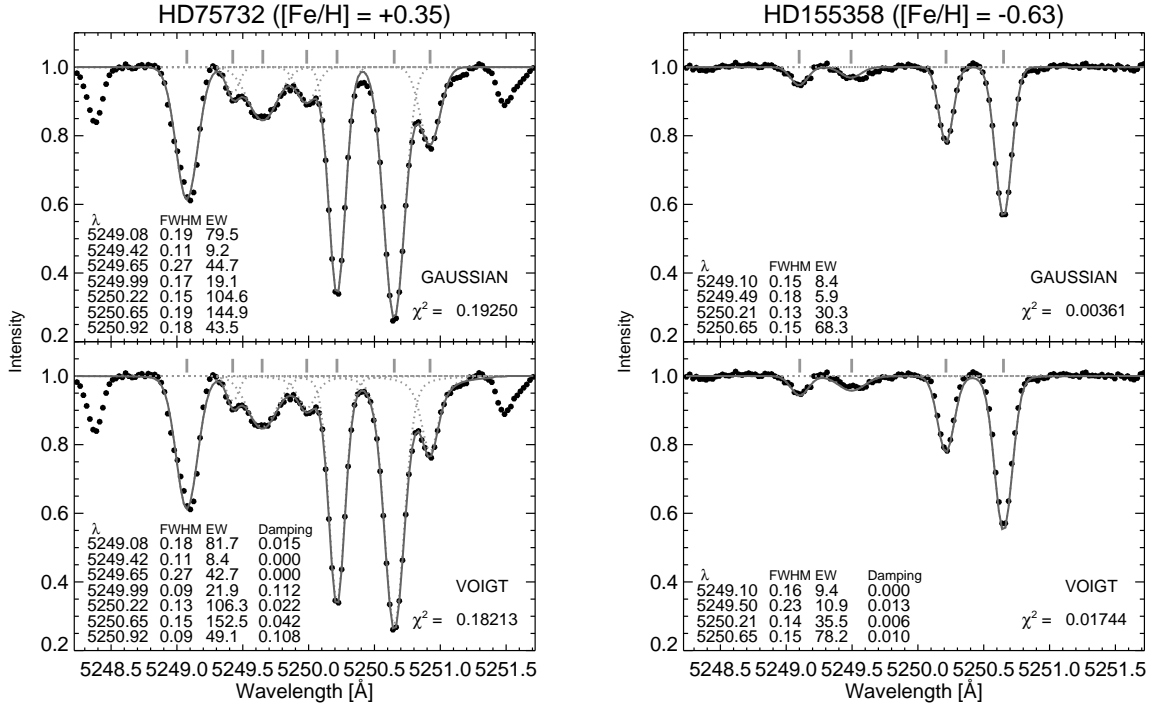


Fig. 6.— The line detection and fitting results of HD 75732 and HD 155358. The *black* dots represent the observed spectrum, and the *gray* vertical thick lines indicate the positions of detected lines. The *gray* dotted lines and *gray* solid lines denote the fitting profile for each line and for all the lines, respectively.

spectra, we examined the *EWs* measured by TAME for synthetic spectra having different spectral resolutions and S/N ratios.

#### 4.1. Comparison with Manual Measurements

We estimated the solar *EWs* of atomic lines using TAME and IRAF `splot` task. The high-resolution spectrum of the Sun has been obtained with BOAO Echelle Spectrograph (BOES) and has spectral resolution of  $R = 30000$  and S/N ratio  $\gtrsim 300$ .

Figure 7 shows the result of comparing the *EWs* obtained using IRAF `splot` task and

those estimated by TAME. The average and standard deviation between two  $EW$  results are acceptable at  $-0.69$  and  $1.76$  mÅ, respectively. In the plots of the  $EW$  difference vs. the wavelength and  $EW$ , it appears that the  $EW$  differences depend on the wavelength and have no dependence on the  $EW$ . At a short wavelength ( $\lesssim 5500$  Å), as shown in Figure 7b, the difference in the  $EW$  measurement decreases to  $-5$  mÅ and becomes more scattered. This is largely owing to the local continuum determination in the crowded region, where TAME cannot avoid the undersampling of fitting points. The undersampling of valid points reduces the local continuum level and can cause the underestimation of  $EW$ s. In the comparison between TAME and IRAF `splot` task, we did not manipulate the automatic measurement in order to validate the automatic process used in TAME. The underestimated  $EW$ s in a crowded region of spectra could be rectified in the interactive mode, by adjustment of the local continuum level.

We derived the atmospheric parameters of the Sun from the two sets of  $EW$ s obtained by IRAF and TAME. Using the Fe I and Fe II lines, we performed the fine analysis, which employs the dependence of abundance on the excitation potential and  $EW$  of each line and the abundance difference between neutral and singly ionized lines. We adopted MOOG code and Kurucz ATLAS9 model grids (Kurucz 1993; Castelli & Kurucz 2004) for estimating the abundance of each iron line. The result of the fine analysis is shown in Figure 8. We obtained the atmospheric parameters of the Sun as  $T_{\text{eff}} = 5788$  K,  $\log g = 4.49$  dex,  $[\text{Fe}/\text{H}] = 0.00$  dex, and  $\xi_t = 0.96$  km s $^{-1}$  from the  $EW$ s measured by IRAF. Those derived from the  $EW$ s obtained using TAME are  $T_{\text{eff}} = 5791$  K,  $\log g = 4.54$  dex,  $[\text{Fe}/\text{H}] = 0.03$  dex, and  $\xi_t = 0.81$  km s $^{-1}$ . The atmospheric parameters derived from the  $EW$ s measured by TAME are in a good agreement with those derived from the  $EW$ s measured manually using IRAF `splot` task.

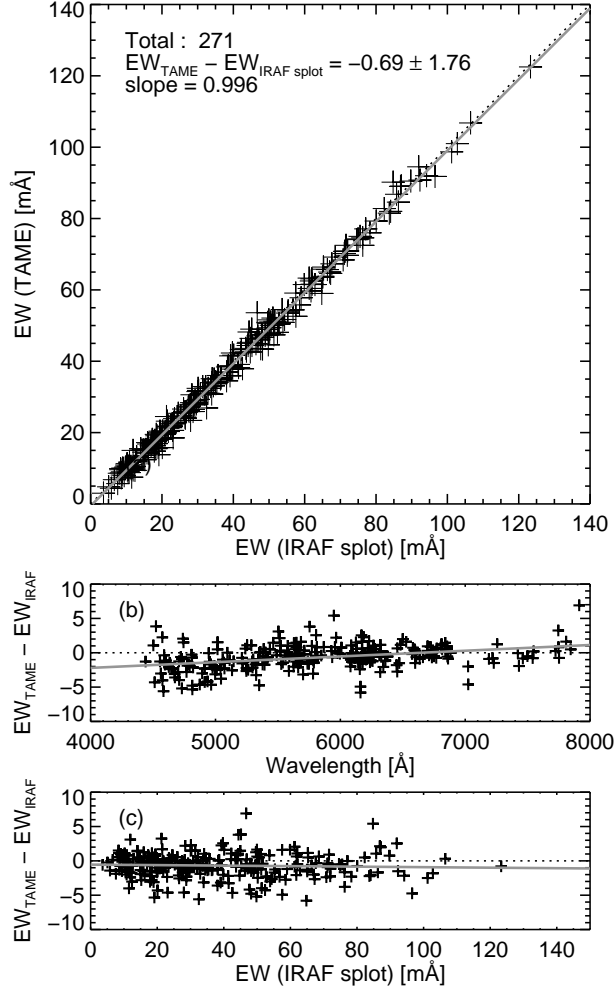


Fig. 7.— The comparison between the  $EW$ s measured by IRAF `splot` task and those obtained using TAME. The *top* panel shows the difference between the two measurements, and the *middle* and *bottom* panels show the trends in the  $EW$  differences along the wavelength and  $EW$  for each line.

#### 4.2. Test with Synthetic Spectrum

$EW$  measurement is obviously sensitive to the quality of the spectrum, or in other words, the errors in  $EW$  measurement depend on the S/N ratio as well as the spectral

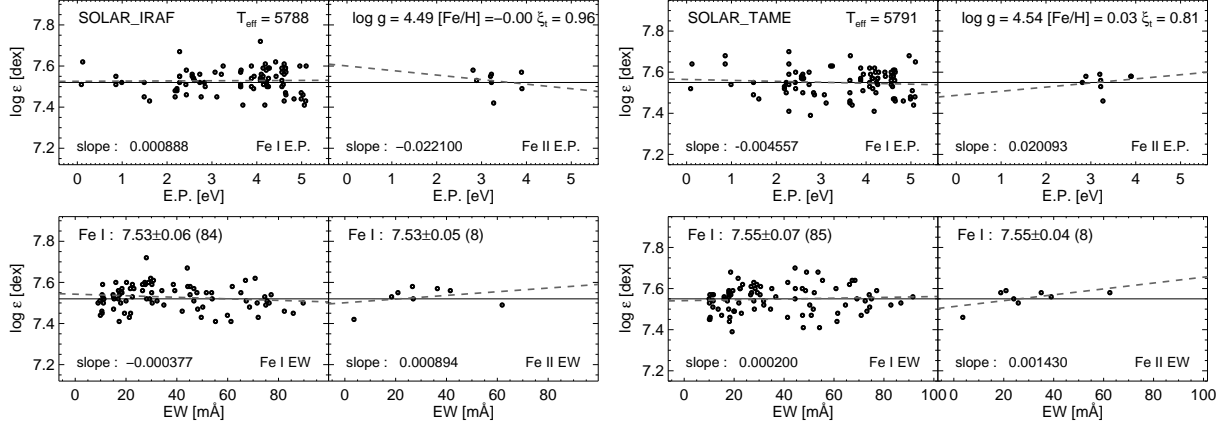


Fig. 8.— The results of the fine analysis performed using the *EWs* of the Fe I and Fe II lines. The four plots on the *left* side show the abundances obtained from the *EWs* measured by IRAF `splot` task and the plots on the *right* show those obtained using the *EWs* measured by TAME. The dashed lines denotes the linear fitting results.

resolution of the spectrum. Therefore, we considered the result of *EWs* measured by TAME for synthetic spectra with different S/N ratios and spectral resolutions. For assessing the reliability of *EW* measurement on the different spectra, we used the synthetic spectra with S/N ratios of 50, 100, 150, 200, and 300, and spectral resolutions  $R = 5000, 10000, 20000, 50000$ , and  $100000$ . We then measured the *EWs* of the lines for each synthetic spectrum in the automatic mode; that is, we obtained the *EWs* using TAME without any interactive operations. Figure 9 shows three examples of input and measured *EWs*. Compared with Figure 9a, Figure 9b indicates that the rms of the *EW* difference increases to  $\sim 2.5$  mÅ with a S/N ratio decreasing from 100 to 50, for the same resolution,  $R = 20000$ . When spectral resolution decreases from 20000 to 10000, as shown in Figure 9c, the *EWs* of weak lines appear to be underestimated by TAME. The underestimation of *EW* at a low spectral resolution will be discussed further together with Figure 10.

In order to investigate the variation in the *EW* measurement resulting from the

properties of the spectrum, we calculated the detection rate of lines and the difference between input and measured  $EW$ s for each S/N ratio and each spectral resolution. As shown in Figure 10, we found that the  $EW$  difference between the input and measured values converged rapidly to zero when the spectral resolution increased (especially,  $R \gtrsim 20000$ ) and less sensitive to the noise in the spectrum. Similarly, as the amount of the  $EW$  difference increased, the detection rate also decreased with a decreasing spectral resolution. The average  $EW$  difference sharply decreased below  $-15 \text{ m}\text{\AA}$  at low resolution of  $R = 5000$ , and particularly, in the case of S/N ratio = 50, the  $EW$  difference reduced to  $-25 \text{ m}\text{\AA}$ . This is because TAME is likely to deblend the target line into arbitrary several lines in the spectrum with a low resolution. The depth of the absorption line becomes more shallow when a spectral resolution decreases, and hence the noise patterns can be confused with a feature of absorption line in numerical line identification. This also explains why the detection rate decreases at a low spectral resolution. However, excessive deblending by TAME can be reduced by using a large SMOOTHER parameter in most cases. From the data in Table 1, we could confirm that using a higher SMOOTHER parameter ( $= 5$ ) causes the detection rate to become much higher and the average difference further stabilizes even for a low resolution of  $R = 5000$ .

From this assessment, we conclude that TAME is reliable for measuring the  $EW$ s in the spectrum of a typical high-resolution echelle spectrograph, which has a spectral resolution of  $R \gtrsim 20000$ , and the rms result indicates that the error in the  $EW$  measurement reduces to less than  $1 \text{ m}\text{\AA}$  for a S/N ratio  $\gtrsim 100$ .

## 5. Summary

We have developed a new software tool for automatic  $EW$  measurement called TAME for measuring  $EW$ s in a high-resolution spectrum. It has the following features:

Table 1. Line detection ratio and statistics of the difference between the input and measured  $EW$ s for different spectral resolution and S/N ratio values of synthetic spectra

Resolution	SNR	SMOOTHER = 3			SMOOTHER = 5		
		Detection[%]	Avg. [mÅ]	rms [mÅ]	Detection[%]	Avg. [mÅ]	rms [mÅ]
5000	50	73.80	-25.978	18.528	68.63	-16.308	12.448
5000	100	74.17	-23.656	17.121	86.35	-10.704	10.558
5000	150	73.43	-23.907	18.177	88.19	-6.856	6.990
5000	200	70.85	-22.461	16.869	90.77	-4.000	8.271
5000	300	67.53	-18.683	15.031	92.25	-2.275	7.715
10000	50	92.99	-7.200	7.317	92.62	-1.846	3.309
10000	100	96.31	-3.081	4.078	98.15	-0.486	1.588
10000	150	96.68	-2.018	3.242	99.26	-0.192	0.937
10000	200	97.79	-1.138	2.399	98.89	-0.092	0.572
10000	300	98.15	-0.463	1.585	99.26	-0.001	0.456
20000	50	98.52	-0.001	2.468	98.52	0.163	1.929
20000	100	99.26	0.032	0.790	99.63	0.041	0.799
20000	150	99.26	-0.046	0.504	99.26	-0.042	0.504
20000	200	100.00	0.030	0.434	100.00	0.030	0.435
20000	300	99.63	0.036	0.283	99.63	0.037	0.283
50000	50	99.26	0.013	1.400	99.26	0.012	1.398
50000	100	99.63	0.060	0.689	99.63	0.060	0.691
50000	150	99.63	0.053	0.441	99.63	0.054	0.442
50000	200	99.63	0.064	0.338	99.63	0.064	0.335
50000	300	99.63	0.069	0.269	99.63	0.069	0.268
100000	50	99.26	0.182	1.279	99.26	0.180	1.278
100000	100	100.00	0.048	0.711	99.63	0.055	0.771
100000	150	99.26	0.094	0.533	99.26	0.093	0.537
100000	200	99.26	0.081	0.453	99.26	0.082	0.451
100000	300	99.26	0.097	0.362	99.26	0.096	0.365

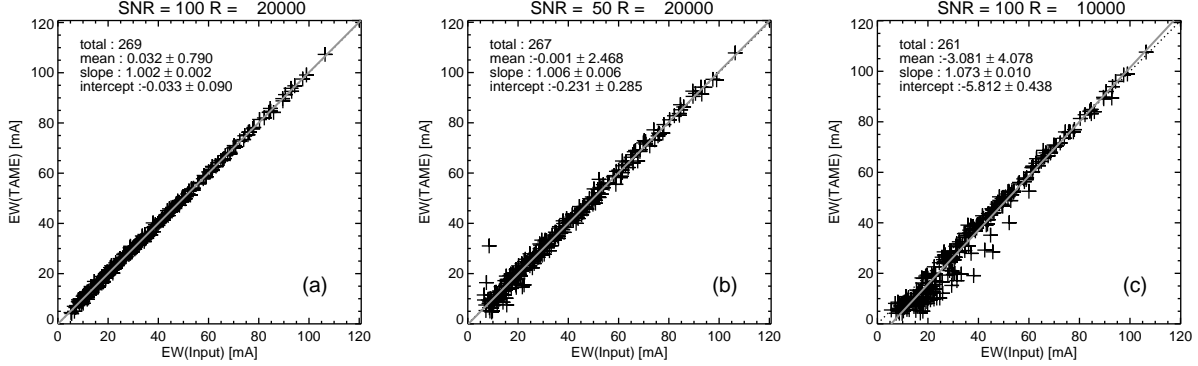


Fig. 9.— The sample plots of the input  $EW$ s for the synthetic spectra and those measured by TAME. The plots show the results for three different kinds of synthetic spectra, which have  $(\text{SNR}, R) = (100, 20000)$ ,  $(50, 20000)$ , and  $(100, 10000)$  in the case that the SMOOTHER parameter = 3. The plot in the *middle* represents the example of a low S/N ratio, and the plot in the *right* shows how the  $EW$  measurement changes when spectral resolution decreases with respect to the plot on the *left*.

- TAME can automatically measure  $EW$ s for a large set of lines in a spectrum simultaneously.
- TAME offers an interactive mode, in which a user can adjust the local continuum level precisely and change parameters such as the SMOOTHER, radial velocity, and type of fitting profile (Gaussian/Voigt).
- TAME provides a text file including the  $EW$ s with a format suited for MOOG code and a graphical post-script file for confirming the  $EW$  results when performing abundance analysis.

We verified TAME in two ways. By using the solar spectrum, we measured solar  $EW$ s by TAME and compared them with those obtained by the traditional method with IRAF `splot` task. The  $EW$ s measured by TAME showed a good agreement with the precise

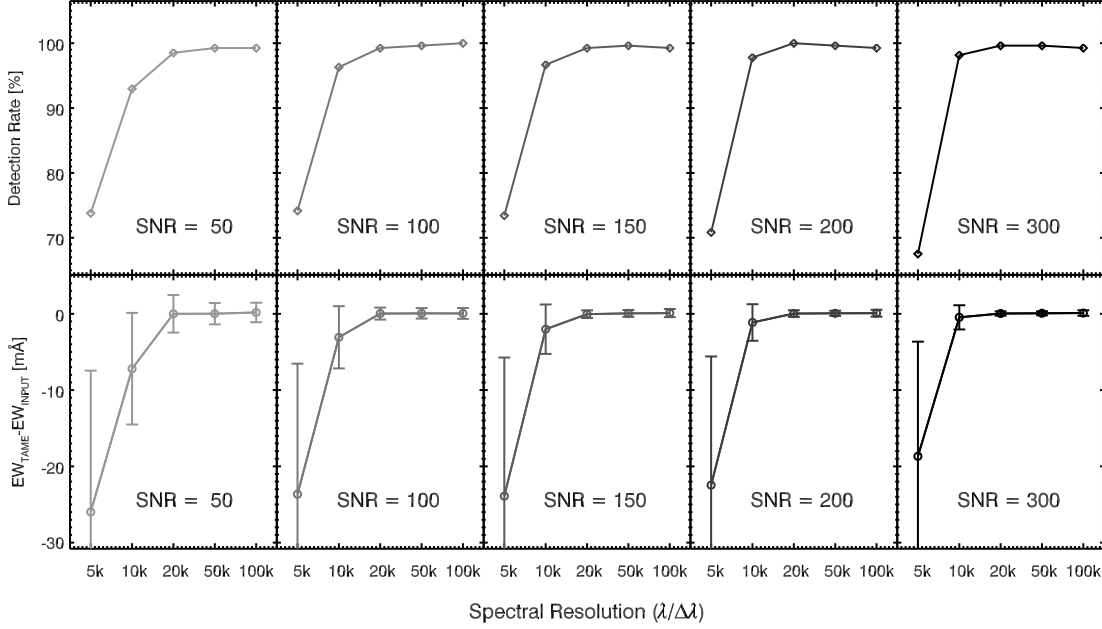


Fig. 10.— The detection ratio of lines and the difference between the input and the measured  $EW$  by TAME (for SMOOTH = 3). The error bars in the *lower* plots represent the standard deviation of  $EW$  differences for each spectral resolution and each S/N ratio.

manual measurements made using IRAF, with a standard deviation of only 1.76 mÅ, and the atmospheric parameters of the Sun were determined to  $T_{\text{eff}} = 5791$  K,  $\log g = 4.54$  dex,  $[\text{Fe}/\text{H}] = 0.03$  dex, and  $\xi_t = 0.81$  km s<sup>-1</sup> from the  $EW$  result of TAME.

In order to examine the effect of the S/N ratio and spectral resolution on  $EW$  measurement, we performed  $EW$  measurement for different synthetic spectra by using TAME in the fully automatic mode without any manual interactions. From the test results obtained for the synthetic spectra, we concluded that the  $EW$  measurements obtained by TAME are reliable for high-resolution spectra with  $R \gtrsim 20000$  and found that the errors in  $EW$ s could be expected to be less than 1 mÅ for a S/N ratio  $\gtrsim 100$ .



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